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DESIGN STUDY OF A LARGE AREA CYLINDRICAL
ELECTRON GUN

William H. Sain

EIMAC

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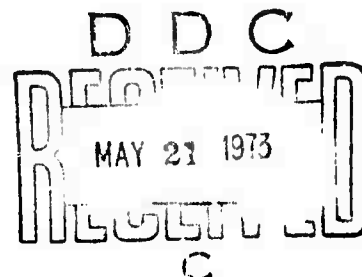
DESIGN STUDY OF A
LARGE AREA CYLINDRICAL ELECTRON GUN

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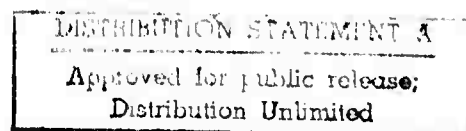


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| 13. ABSTRACT This study was concerned with the design of a large cylindrical electron gun (5 meters long by 1 to 2 meters in diameter) & the application of state of the art high power electron tube technology to this design. A design which applies welded thoriated tungsten mesh cathodes and refractory metal grids (as used in power tubes) was investigated. Vibration characteristics of prototype mesh filaments were calculated & measurements of filament resonant frequencies confirmed the predictability of the behavior of mesh filaments. Experiments were performed on titanium foil windows which were diffusion bonded or brazed to cylindrical sealing members. These were vacuum tight after high temperature bakeout and confirmed the feasibility of fabricating modular, bonded electron window structures. | | | |
| Details of illustrations in this document may be better studied on microfiche | | | |

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1.0 OBJECTIVES

To conduct a design study of a large area cylindrical electron gun for excitation of a high power pulsed electron beam stabilized electric discharge laser. This study includes analysis of the electrical, mechanical, and thermal factors affecting the performance of such a gun. The operating conditions were to be in the following range:

| | |
|---------------------------------------|-----------------------|
| Electron Current Density of output | .01 amperes/sq.cm. |
| Accelerating Voltage | 100 to 200 KV |
| Pulse Length | 10 to 30 microseconds |
| Pulse Repitition Rate | 10 to 30 pps |
| Electron Beam Dimension: | |
| Diameter | 1 to 2 meters |
| Length | 5 meters |

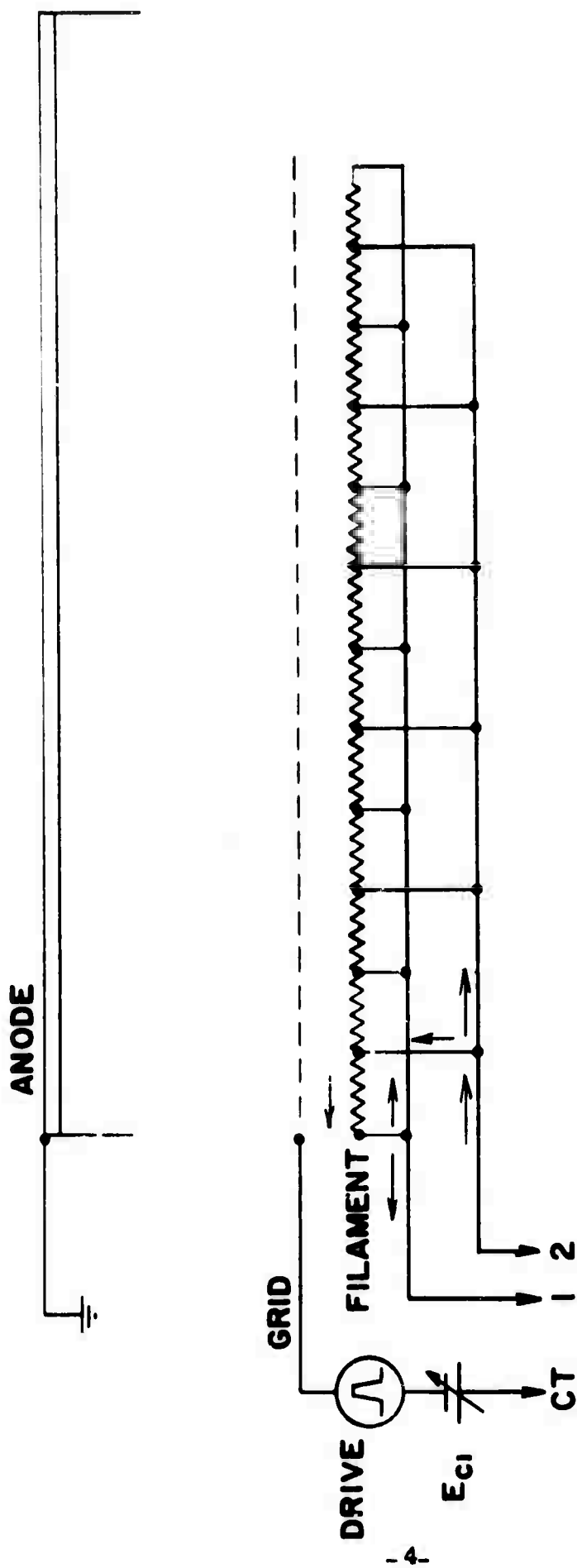
2.0 NARRATIVE AND DATA

Design of the Cylindrical Electron Gun.

Two candidate designs have been investigated. These are, first, a coaxial, cylindrical structure with cylindrical mesh filament emitters and grids, mounted on a coaxial water-cooled "strongback" made of tubing. The second approach is the use of rectangular segments with parallel bar filaments and grids, forming a prismatic core and bolted together using heavy flanges to connect the elements to each other and to an end support/insulator assembly.

The coaxial cylinder mounting has weight advantages and can be made with a high stiffness under gravity loads. It is shown in its simplest form in Figure 1; basically a pair of tubes of high strength, thin wall tubing, the outer one carrying a thin water wall for cooling. Each tube carries filament current in a balanced configuration as shown in the diagram, Figure 2. The direction of current flow in the filament is indicated by the arrows. In this arrangement, currents in each conductor and the filament are always in balance; and there is very little magnetic field contributed by the filament current. (This is restricted to the localized field in the immediate vicinity of a filament wire).

The magnitude of the filament current (several thousand amperes) is such that the coaxial filament conductors must be made of a non-magnetic material with good electrical conductivity. The cupro-nickel alloys with 10 to 30 percent copper content



TO AC FILAMENT SUPPLY
AND -HV

**SCHEMATIC OF CYLINDRICAL TRIODE ELECTRON
GUN SHOWING FILAMENT CONNECTIONS**

combine good strength, fabricability and electrical conductivity, and large diameter thin wall seamless tubing is available in this material. Thoriated-tungsten mesh filaments are used with junctions between sections connected alternately to the coaxial conductors. Connection to the inner conductor is made via flexible connectors which allow relative expansion between the support tubes. The filament and grid sections are mounted independently on rail assemblies which are assembled one by one on the outer support cylinder.

The grid(s) will be mounted on ceramic insulating parts attached to support rails, external electrical connection to the grid is made at the outer end of the assembly.

Electron Emitters

The choice of an electron emitter suitable for large scale electron guns is one which is dictated primarily by scale (the size requirement) and by the environment in which it must operate. The criteria which were used for selection of cathode materials and methods of construction are listed below:

1. Must uniformly irradiate a cylindrical anode 1 to 2 meters diameter, 5 meters long with 1 to 10 milliamperes per square centimeter during pulses 30 microseconds long.
2. Furnish .0140 amperes peak emission unsaturated.
3. Operate in 10^{-7} , or worse, vacuum.
4. Withstand arcing and breakdowns during high voltage conditioning and operation.

5. Be economical in use of heating power, (250KW maximum).
6. Withstand repeated shock excitation, e.g., 2g peak at 1 to 10 pps, in either longitudinal or transverse mode, at supports.
7. Be resistant to occasional operation in a flood of CO₂, N₂, He gas mixture (after anode puncture) for brief times until the cathode can cool.

A brief discussion of the cathode types which were considered follows:

Oxide Cathode

The oxide cathode, which is a thin coating of a mixture of barium and strontium oxides, and sometimes, calcium oxide, on a base metal such as nickel, provides the highest emission efficiency in terms of amperes available emission per watt of heating power of any of the commonly used thermionic emitters. However, it is extremely susceptible to poisoning by oxygen and oxygen-containing gases and cannot be repumped and reactivated once exposed to an injurious atmosphere.* It is expected that leaks in the target foil will occur frequently and a relatively high background pressure of oxygen-containing gases is to be expected. For this reason, oxide cathodes were rejected as an electron source in the cylindrical electron gun.

*Redhead, P.A. and McNarry, L.R., "The Emission Life of Oxide Cathodes", Nat. Res. Council of Canada, ERA-229, 1952.

Tungsten Matrix Cathode

A cathode which combines good emission efficiency high current density capability with a moderate degree of resistance to gas poisoning is the tungsten matrix cathode. It consists of a sintered porous core of tungsten metal, impregnated with an emitting compound. The most commonly used impregnant is barium aluminate, the "Type A" dispenser cathode, or with the addition of calcium aluminate, "Type B" dispenser cathode. These cathodes are capable of providing 1 to 10 amperes of useful electron emission per square centimeter at 1000 to 1100 degrees centigrade. These are thin film emitters which depend on the low work function of a barium layer on the tungsten surface and are much used in UHF amplifier electron tubes, particularly in linear beam tubes, and planar triodes.

Impregnated tungsten cathodes are sensitive to poisoning by positive ion bombardment, oxygen and carbon or organic compounds. To a limited extent, emission can be restored after poisoning by heating to 1100°C for a few hours. However, longer activation times and higher temperature may be necessary on repetition of the activation process.

Among the disadvantages of the dispenser cathode are the following.

1. A high rate of evaporation of barium metal at normal operating temperatures, The barium condenses on cooler surfaces contributing to grid emission and voltage breakdown across insulators.

2. The substrate is porous tungsten fabricated in blocky shapes and ground to finished size. Limitations on maximum size would require use of many pieces distributed over the surface of a cathode such as we are considering. A complex supporting structure would be required.
3. The dispenser cathode must be indirectly heated. Although heaters can be molded into the cathode pellet, the large number of complex parts and connections required would detract from the reliability of the cathode assembly.

Metal Cathodes

Pure metals have been extensively used for emitters; particularly W, Ta, Mo and Re, with tungsten the traditional favorite for power electron tubes. Among the metallic emitters, tungsten has the best combination of strength and vapor pressure at emission current densities above 0.1 amperes per square centimeter. Tungsten cathodes are usually directly-heated wire filaments supported in tension to avoid sag. Using fine wire, tungsten filaments can be distributed over a large surface area without causing "holes" in the electron beam (for example, as in "squirrel cage" vacuum tube cathodes). However, tungsten filaments are not noted for either mechanical ruggedness or emission efficiency.

Thoriated tungsten has been used for thermionic cathodes for the past 40 to 50 years. Extensive use in power tubes began 35 years ago with the improvement of processing techniques and the introduction of refractory getter materials in power tube manufacture. It has largely replaced pure tungsten because carburized thoriated tungsten is more efficient in the use of heating power, operates at a considerably lower temperature and has much longer life.

The tungsten base material (usually in wire form) has thorium oxide particles of micron-to-submicron size distributed throughout the volume. These particles, originally introduced to strengthen tungsten, largely remain in the original form. A small fraction of the thorium is reduced to thorium metal and diffuses to the surface and partially covers the surface, giving rise to electron emission characteristic of thorium metal films. If a layer of tungsten carbide is formed on the filament surface, this layer of carbide controls rate of production of thorium and diffusion of the thorium to the surface of the filament. Typically, the useful life of the filament is then determined by the time at which all carbon is lost by combination with tube gas or by thermal decomposition. The filament can be revived by recarburization.

The operating life of power tubes with carburized thoriated tungsten filaments is measured in tens of thousands of hours at high emission current density (typically 1 ampere per square cm).

The cathodes are very resistant to damage by ion bombardment and accidental or brief exposure to gases at moderate pressures.

Operating temperatures are in the range of 1800 to 2000 degrees Kelvin, and fabrication techniques are such that large, low density, welded filament structures will resist damage from mechanical shock and vibration. Therefore, the design analysis has been concentrated on the carburized thoriated-tungsten filament.

Grids

The electrodes which control the flow of electrons in an electron gun must be stable, i.e., retain their shape and spacing relative to other parts of the gun. There are mechanical stresses imposed on the grids, consisting of gravity loads, thermal expansion forces against mounting restraints and vibration and shock coupled through the gun mounting means. These requirements for mechanical ruggedness are in conflict with the desired electrical qualities. The ideal grid from an electronic point of view is one which creates a uniform electric field and intercepts none of the cathode current. In practice it is usually a grating of fine wire uniformly distributed across the electron beam in tubes with large area electron beams. Current grid designs at EIMAC are largely "squirrel-cage" welded wire cylinders in which a helix of fine molybdenum wire is wrapped around longitudinal wires of the same size (0.005 inch diameter to 0.025 inch diameter) in a continuous helix. The pitch of the helix is 1 to 4 times the pitch of the axial wires); thus

the openings of the grid are square to rectangular. Each crossing of helix and axial bar is welded. The resulting cage is surprisingly strong and light and very resistant to thermal deformation and to shock and vibration. These grids are made in sizes up to 8 inches diameter by 16 inches long. A grid of the larger size is shown in Figure 3. The maximum size of such a grid is not known; however, one 20 inches in diameter is deemed feasible. Several sections, each one up to 2 feet long, could be assembled in series to make up a 5 meter long grid assembly. Intermediate ring supports to which the ends of each section are fastened would assure that the grids remained round and did not sag.

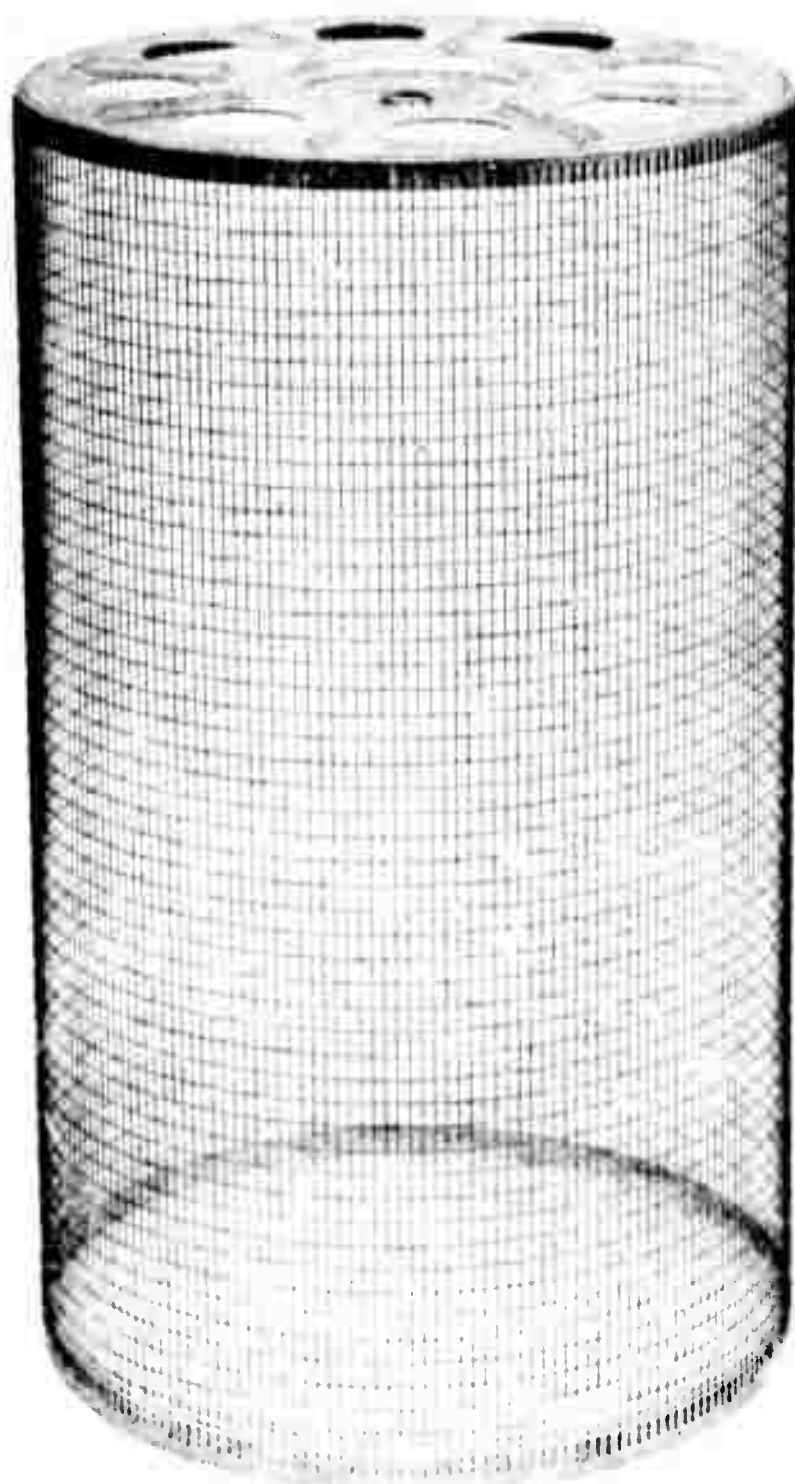
Grid Current

A major grid-associated problem in electron tubes and guns is that of grid currents. These currents are, variously:

1. Intercepted electron current
2. Secondary emission current
3. Primary emission current
4. Ion current
5. Photo-emission current

and the list could be extended further.

The intercepted electron current is determined largely by the mechanical design of the grid and the operating voltage, and is responsible for a part of the total heat input to the grid, but is little affected by choice of materials or by processing techniques. In a low duty pulsed application the intercepted component



EIMAC

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FIGURE 1. EIMAC FILTER

of grid current is not a major concern.

The last two named current components are largely controlled by influences external to the grids such as quality of vacuum, anode current density and electron energy at the anode. However, gas ion grid current is often used as an indicator of vacuum quality.

The primary and secondary electron emission currents are of importance in switch tubes. The magnitude of these currents is determined by the condition and composition of the surface of the grid and the operating temperature of the grid, and are often at a level which restricts the power handling capability of an electron tube or can cause failure of equipment. The undesirable effects of these currents (which are negative in sign and often rise exponentially with voltage) are:

1. Loading of the input circuit and loss of gain.
2. A tendency to change sign of the net grid current to a positive grid, causing blocking, voltage runaway and oscillation or ringing in the input pulse.
3. Damping of the output circuit and loss of power output.
4. Interpulse and intrapulse ("dark current").

Primary grid emission is a consequence of the grid becoming heated while contaminated with material of a low work function. The heat is contributed by radiation from a hot cathode and by intercepted electrons; the contamination is usually cathode evaporants. This current usually increases as emissive material evaporates from the cathode and deposits on the grid.

Because of the scaling requirements of high frequency operation (lengths inversely as frequency, current density and power density as frequency squared),* the grids tend to have small structural members which are hard to cool by conduction and are more apt to emit thermionically. The materials must be refractory metals, generally tungsten or molybdenum, for strength and mechanical stability at high operating temperatures. These make excellent thermionic emitter bases when coated with barium, thorium, or other good emitters, and generally have surfaces heated to reduce emission when contaminated by cathode evaporants.

Secondary electron emission is the result of bombardment of a surface by energetic electrons. The magnitude is characterized by the secondary emission ratio $\delta = I_{\text{pri}}/I_{\text{sec}}$ and by the variation of the ratio with the energy of the bombarding electrons. The maximum of this ratio δ_{max} and the energy at this ratio, E_{max} , are of interest.

The commonly used grid and grid coating materials, such as W, Mo, Au (platings), Pt, and Ta, have δ_{max} of 1.25 to 1.8 ** with E_{max} in the range of 400 to 800 volts. Exceptions are Titanium and Carbon which have δ_{max} of 0.45 (soot) to 1.0 (graphite) and 0.9 (Ti). These values are for smooth, clean surfaces. A coating of Barium Oxide has a very high δ_{max} , 2.3 to 4.8 whereas for Barium metal it is 0.8.

*A.H.W. Beck, "Thermionic Valves", Cambridge University Press, 1953, p. 213, 214.

**Handbook of Chemistry & Physics, The Chemical Rubber Co., Cleveland, Ohio. 1971

and maintenance of tight controls on the heater voltage. These are common practices in the design and operation of power tubes.

The emitting material on the grid surface can be made non-emitting by reactions with materials on the surface, or can be electrochemically or thermally reduced to a state which can be eliminated by diffusion into the substrate or by evaporation. The special grid coatings, of various types, are designed to perform these functions. Some have other characteristics which lower grid emission such as high thermal emissivities, and low secondary emission coefficient. These are selected for their special properties depending on the type of cathode used, the power density, construction methods, cost, etc.

Grids for Thoriated Tungsten Cathodes

Tubes which employ thoriated tungsten or pure tungsten cathodes most often employ grids which are coated with platinum combinations. These last are usually applied in the form of rough coatings sintered to the molybdenum or tungsten wire. They effectively suppress secondary and primary emission and operate in the temperature range 700 to 1300°C, and are cooled by thermal radiation.

EIMAC has been a leader in the technology of these grids and of thoriated tungsten power tubes. EIMAC holds numerous basic patents on grid coating and processing, and sells coated grid wire to other manufacturers.

Very rough surfaces have low values of secondary emission. The secondary electrons are trapped by surface cavities and δ_{max} can be reduced to less than 0.5, as shown by Rashkovskii.*

Reduction of Grid Emission in Power Tubes

Three techniques are commonly used to reduce grid emission current. They are:

1. Reduce operating temperature of the grid.
2. Increase the work function of the grid surface by poisoning the emission of the contaminating emitting material.
3. Reduce the amount of emitting material on the surface of the grid wire.

Operating temperature can be reduced by increased thermal conductivity of grid supports, blackening grid wires and structures where radiation cooling is of importance, and designing for minimum interception of electrons by positive-going grids. These steps are taken in the initial tube design and are usually time invariant.

The deposit of emitting material, (i.e., cathode evaporant) on the grid can be reduced by choosing cathode materials for low evaporation rates, by operation at minimum cathode temperatures

*S.F. Rashkovskii, "Secondary Emission from Rough Surfaces". Radio Eng., & Electronics, V3, n.3, 1958, pp 970118.

Properties of Thoriated Tungsten

The temperature dependent properties of a carburized thoriated tungsten filament are summarized below:

1. Radiance:

$$\rho = 3 \cdot 10^{-16} T^{5.14} \text{ watts/sq.cm.}$$

2. Specific resistance:

$$\rho = 4.9 \cdot 10^{-9} T^{1.25} \text{ ohm cm}$$

3. Electron emission density (zero-field):

$$j_s = AT^2 \exp - 11,600 \phi/T \text{ amperes/sq.cm}$$

wherein T = operating temperature, deg. K

A = 1.6 (Richardson constant)

ϕ = 2.53 volts (work function)

These values were obtained from measurements on mesh filaments made in production runs at EIMAC and are within the ranges of published values.

The radiance formula would have the usual fourth power dependence of radiated power density on temperature were it not for the variation (with temperature) of the total emissivity of di-tungsten carbide (W_2C) as described by Barnes. *

The specific resistance was determined by tests on carburized

* Barnes, B.T., "Properties of Carburized Tungsten", J. Phys. Chem, 33, May, 1929, p. 689.

thoriated tungsten filaments, carburized to approximately 12 percent higher resistance than the original resistance, which results in a carbide content, by area, of thirty percent.

The emission density formula is the familiar Richardson equation and has two "constants". The first, Richardson constant "A" is extremely variable, depending on the state of activation of the filament. The second, or work function, is more constant and our value of 2.53 volts agrees well with published values of 2.5 to 2.65 volts, *, **.

Design Calculation

A computer program for calculation of mesh Th-W filament designs was available for the design analysis. In this program, the operating temperature, thermionic emission, degree of carburization, length and diameter of the mesh, and the wire size are specified by the user. The output includes the total operating power, current, and voltage drop, mesh size, fundamental resonance frequency (longitudinal mode) and the number of wire windings required.

The natural resonance frequency is calculated according to the method shown in Appendix A. The correctness of the method was confirmed by experiment.

A set of calculations was run for the cylindrical electron

* Jones, T.J., "Thermionic Emission", Chem. Publishing Co., N.Y., 1936.

**Fomenko, V.S., "Handbook of Thermionic Properties", Pileum Press, N.Y., 1966.

gun cathode. The following set of input parameters were used:

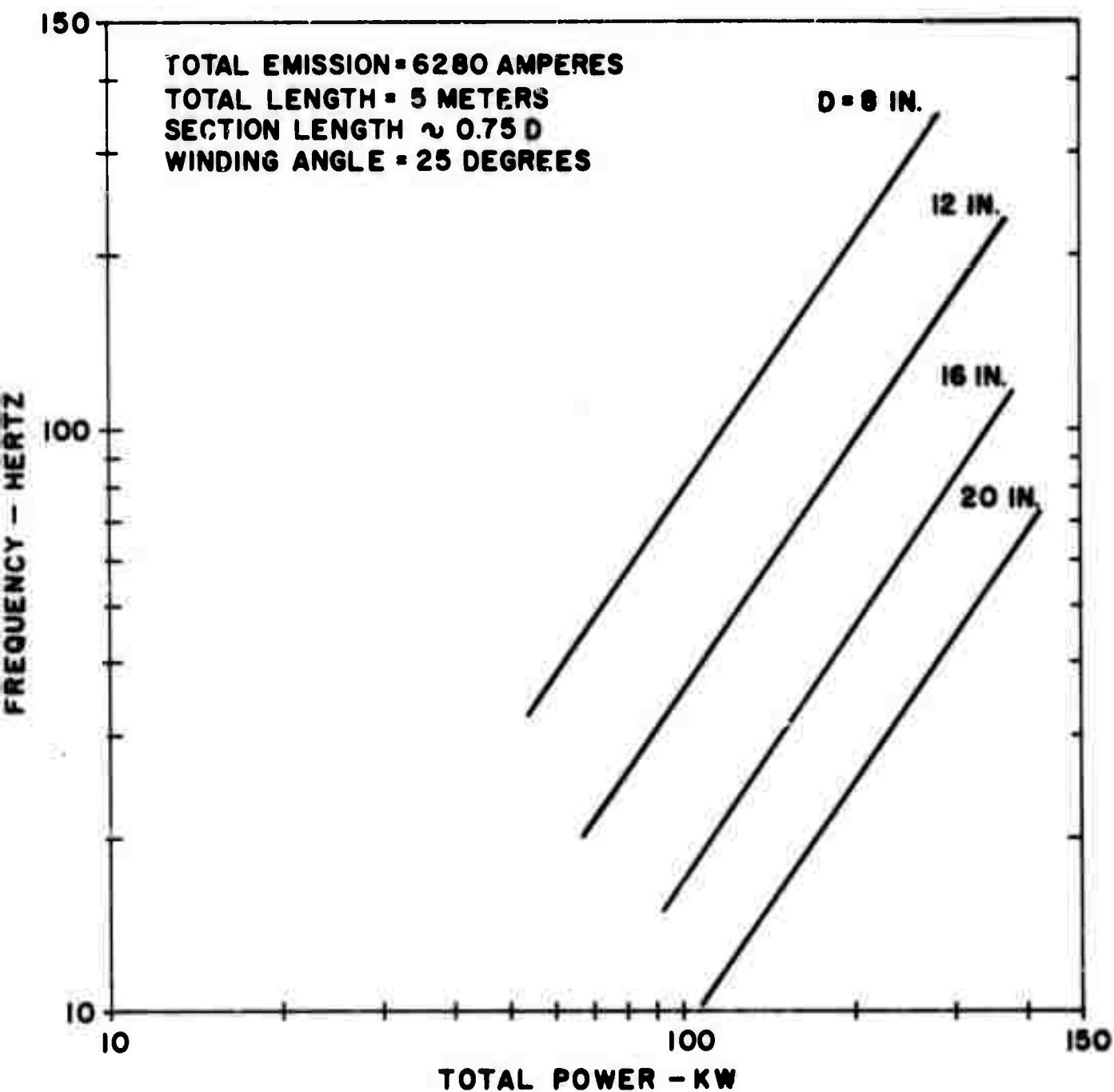
1. Total emission current of 6280 amperes, to give an incident anode current density of 0.020 amperes per square centimeter on an anode 2 meters diameter and 5 meters long.
2. 6 percent carburization (15 percent by area).
3. 25 degree winding angle (following EIMAC practice for large tubes).
4. Filament sections 8 to 20 inches diameter with a 0.75 length-to-diameter ratio.
5. Operating temperatures of 1800 to 2025 degrees Kelvin in 25 degree K steps.
6. Wire diameter of 0.008 inch to 0.020 inch in 0.002 inch steps.

In computing the emission density at the operating temperature, a value of 1.0 was used for the Richardson constant A in equation 3, to allow for less complete activation of the filament.

Results of the calculations:

Our interest is in four areas. These are: first, high fundamental resonant frequency (well above 10 Hertz), second, low operating power; third, fabricability, and fourth, electrical performance.

Figure 4 is a summary of the results for four different cathode diameters, showing fundamental resonance as a function of total power input to the cathode. We find that, for a fixed cathode diameter, (hence section length), the frequency rises with power.



**LONGITUDINAL RESONANCE FREQUENCY FOR
MESH CATHODE**

FIG. 4

The relationship is approximately the following:

$$f_1 \text{ (Hertz)} = a P^{1.43}, \quad P \text{ in kilowatts}$$

For the 8 inch diameter cathode, the value of 'a' is 0.106.

The frequency is also dependent on the choice of diameter, and, for fixed diameter/length ratio, is proportional to the inverse square of diameter. For an operating temperature of 1950K with an input power of 134 kilowatts the frequency is:

$$f_1 \approx \frac{11000}{D^2 \cdot 16} \text{ Hertz, } D \text{ in inches}$$

The exponent of D is slightly greater than 2.0 because of the effect of end cooling on wire length.

For any individual mesh filament section, of length 'A' inches, diameter 'D' inches, and winding angle θ degrees, the fundamental longitudinal resonance is:

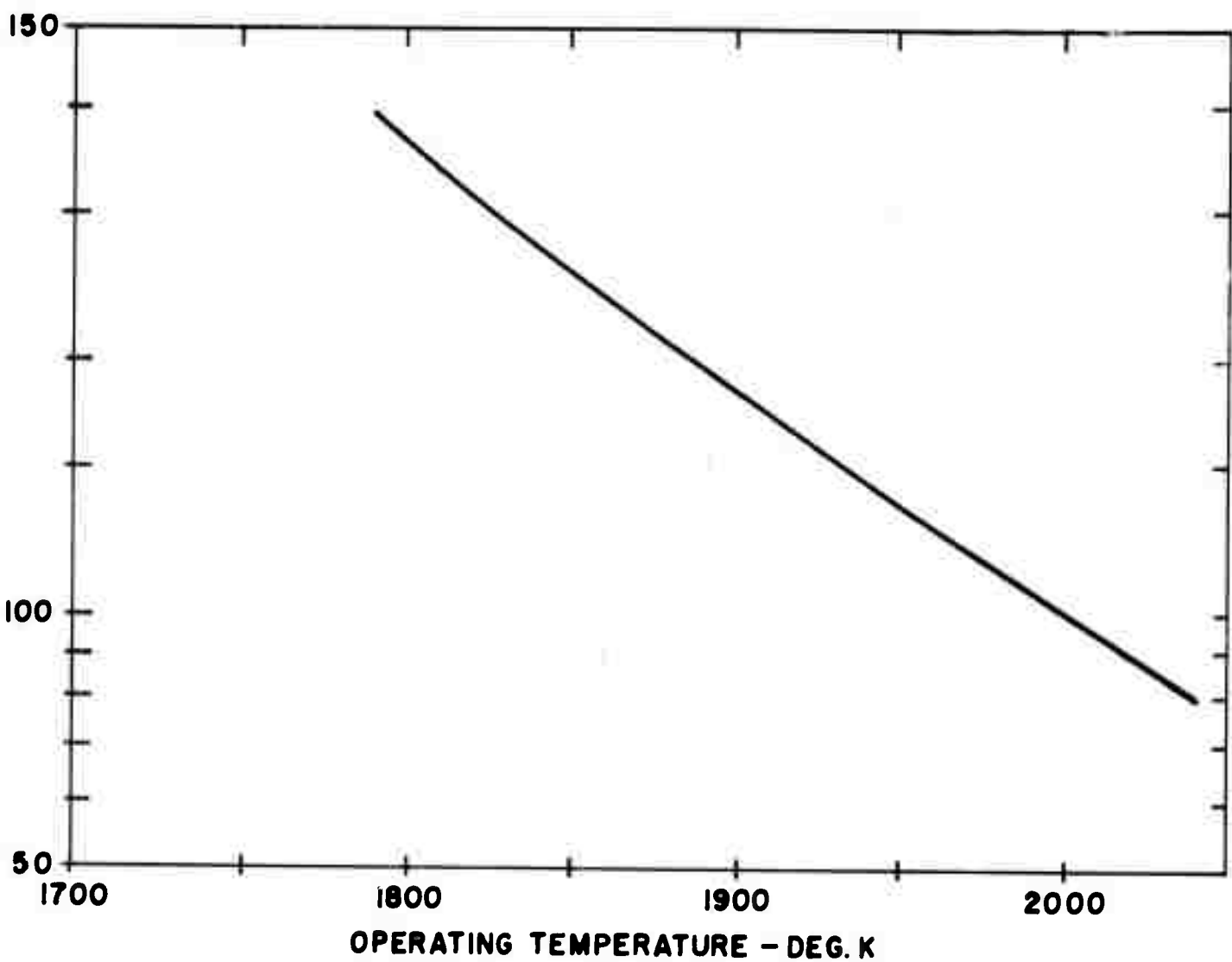
$$F_1 = \frac{7.2 \cdot 10^4}{\pi^2} \frac{I_s}{j_s} \frac{\sin^2 \theta}{H^2 D}$$

where the quotient I_s/j_s is the emitting wire surface area, per section in square inches. It is, therefore, for a specified emission current and operating temperature, independent of the wire size. The reason is that the wire density in the mesh is dependent on the choice of wire diameter and the stiffness-to-mass ratio of the mesh is then a constant.

Heating Power Requirement

The minimum emitting, and radiating, area of the mesh filament, is calculated from the total emission current requirement (taken to be twice the operating current) divided by the emission density at the operating temperature. The total power to heat the filament will be the product of the area and the radiance at this temperature. Figure 5 shows the dependence of total power on temperature at an emission current of 6280 amperes.

To summarize the filament design the characteristics of mesh filaments with a fundamental resonance frequency greater than 55 Hertz, a length of 5 meters, and total emission of 6280 amperes are listed below:



**THORIATED - TUNGSTEN
CATHODE HEATING POWER
 $I_s = 6280$ AMPERES**

FIG. 5

TABLE I

| Pitch Diameter inches | Fund. Frequency Hertz | Section Length inches | Operating Temperature Deg. K | Total Power KW | Number of Sections |
|-----------------------------|-----------------------------|-----------------------------|------------------------------------|----------------------|--------------------------|
| 8 | 77 | 6.0 | 2000 | 100 | 32 |
| 10 | 64 | 7.0 | 1975 | 115 | 28 |
| 12 | 55 | 8.3 | 1950 | 134 | 24 |
| 14 | 59 | 10.0 | 1900 | 184 | 20 |
| 16 | 65 | 12.5 | 1850 | 256 | 16 |

Filament diameters greater than 16 inches require too much operating power and are probably beyond fabrication capability.

The filament diameters less than 12 inches will be unsuitable for two reasons; firstly, lack of space inside for a rigid strong-back support and the necessary connections and mounting means, and secondly, the drift space, grid-to-anode, will saturate at low current density and it will not be possible to attain the required operating current.

The design variables for three filaments with satisfactory operating characteristics are listed below in Table II.

TABLE II
Mesh Filament Dimensions

| <u>Variable:</u> | | | | <u>Unit:</u> |
|--------------------------|------|------|------|--------------|
| Diameter | 12 | 14 | 16 | inch |
| Section length | 8.25 | 10.0 | 12.5 | inch |
| Wire diameter | .012 | .016 | .020 | inch |
| No. of windings/section | 52 | 60 | 76 | -- |
| Mesh Opening (Maximum) | 0.62 | 0.55 | 0.55 | inch |
| Filament Voltage/Section | 21 | 20 | 21 | volts |
| Filament Current/Section | 268 | 454 | 766 | amps |
| Operating Temperature | 1950 | 1900 | 1850 | deg.K |
| F1 | 55 | 59 | 66 | Hertz |
| Number of Sections | 24 | 20 | | -- |

Other factors in the mesh design which must be considered are the operating voltage and current, wire diameter (as it affects facility of manufacture), and the size of the mesh openings.

The operating voltage should be below 20 volts per section, because during carburization in a hydrocarbon gas at low pressure, the applied voltage is roughly double the nominal voltage, and the threshold for damaging arcs occurs at 35 to 40 volts rms at this pressure level. Also, the filament voltage adds to the grid-to-filament voltage during operation and causes a non-uniformity in the anode current distribution. The peak filament voltage should be held to less than 3 percent of the equivalent diode voltage (average potential at the grid plane) if its

contribution to anode current non-uniformity is to be less than 5 percent.

The current should be kept low, to reduce power loss as in the filament supports and magnetic fields in the vicinity of the filament wire.

With respect to mesh dimensions, a small mesh opening is desired so that the mesh surface approximates an equipotential surface giving an electron beam of uniform current density. In practice, we have found that opening widths not larger than 1.5 times the grid-to-cathode spacing are satisfactory.

The equation for space charge limited flow in a cylindrical triode or tetrode is:

$$I_k = G (V)^{3/2} \text{ amperes}$$

where:

$$I_k = \text{Cathode current} = I_p + I_{c1} + I_{c2}$$

$$G = \text{Perveance, a geometrical factor}$$

$$V = \text{Reduced Voltage} = E_{c1} + E_{c2}/M_{12} + E_b/M_{13}$$

$$E_{c1} = \text{Control Grid Voltage}$$

$$E_{c2} = \text{Screen Grid Voltage}$$

$$E_b = \text{Anode voltage}$$

and:

$$M_{12} = \text{Amplification Factor, control-screen}$$

$$M_{13} = \text{Amplification Factor, control-anode}$$

This is an approximation and is valid only if the electron-current flow is space-charge limited in the drift space between cathode and grid and not between grid and anode. In the event that the region between grid to anode becomes space-charge limited, additional current injected into the drift space by the filament-grid diode results in formation of a field free region filled by a cloud of electrons (a "virtual cathode") and the anode current saturates.

If the grid voltage is small compared to anode voltage, the Child-Langmuir law for space charge limited current in a cylindrical diode⁽¹⁾ applies:

$$I = \frac{14.66 \times 10^{-6} E_b^{3/2} L}{r_p \beta^2} \text{ amperes}$$

where r_p is the anode radius, L the length, and β is a function of the ratio of the anode radius to grid radius.

(1) Spangenberg, K.R., "Vacuum Tubes", McGraw-Hill, NY, 1948, p 176.

The initial velocity of the electrons at the grid plane has been neglected because the grid voltage is low compared to the anode voltage.

The grid current of a triode increases rapidly as the operating current approaches the saturation current. The proposed design, with grid radius of 19 centimeters (7.5 inches) will operate at a maximum incident anode current density of 0.020 amperes per square centimeter at an anode voltage above 100KV and an anode radius of 0.75 meters. At 1.0 meters anode radius the accelerating voltage must be at least 150 KV to avoid saturation.

Coaxial Grid Design & Operating Characteristics

Triode and tetrode designs were calculated for mesh filamentary cathodes of 8 to 16 inches diameter and 5 meters long. The criteria used in evaluating the results were the following:

1. Peak positive control grid voltage not to exceed +1500 volts.
2. Grid drive voltage less than 2000 volts.
3. Adequate spacing, control grid-to-cathode and control grid-to-screen grid, for mounting means and insulation. Preferably not less than 0.4 inches (1 cm).
4. Maximum screening fraction (ratio of area of grid occupied by wire to total area) not to exceed 0.25.
5. Maintenance of a non-space-charge-limited condition in the space between the grid (or screen) and the anode at maximum current density.

The equation for space charge limited current flow in a triode is:

$$I_k = G (E_{cl} + E_b/\mu)^{3/2}$$

where:

I_s = cathode current

E_{cl} = Grid voltage

E_b = Anode voltage

μ = amplification factor

G = perveance, (amperes per volt)^{3/2}

The amplification factor and perveance are geometrical factors which are determined by the dimensions of the tube. The grid bias for cutoff of current between pulses will be a minimum of:

$$E_{cc} = -I_b/\mu$$

and the peak positive grid voltage during the pulse will be:

$$E_{c1} = e_g - E_{cc}$$

where e_g is the grid drive voltage.

Therefore the conditions existing at the peak of the pulse are:

$$I_k = G e_g^{3/2}$$

We set I_k at twice the maximum current required to deliver 0.010 amperes per square centimeter at the anode foil:

$$I_k = 0.020 \pi D_a L$$

Using the planar approximation for the perveance (valid because the ratio of grid diameter to cathode diameter is close to 1.0).*

$$G = 2.335 \times 10^{-6} \frac{A}{X^2}$$

wherein A is the area of the cathode, X is the cathode-to-grid spacing.

We have then:

$$0.02 \pi D_p L = 2.335 \times 10^{-6} \frac{\pi D_k L}{\left(\frac{D_g - D_k}{2}\right)^2} e_g^{3/2}$$

Reducing, and solving for e_g :

$$e_g = 418 \frac{D_p}{D_k}^{2/3} \left(\frac{D_g - D_k}{2}\right)^{4/3} \text{ volts}$$

D_g , D_k , D_p are in centimeters.

*Spangenberg, K. R., "Vacuum Tubes", McGraw-Hill, NY, 1948, p 171.

The grid drive characteristics, as a function of cathode diameter and grid-cathode spacing, are shown in Figure 6, for an anode diameter of 1.5 meters.

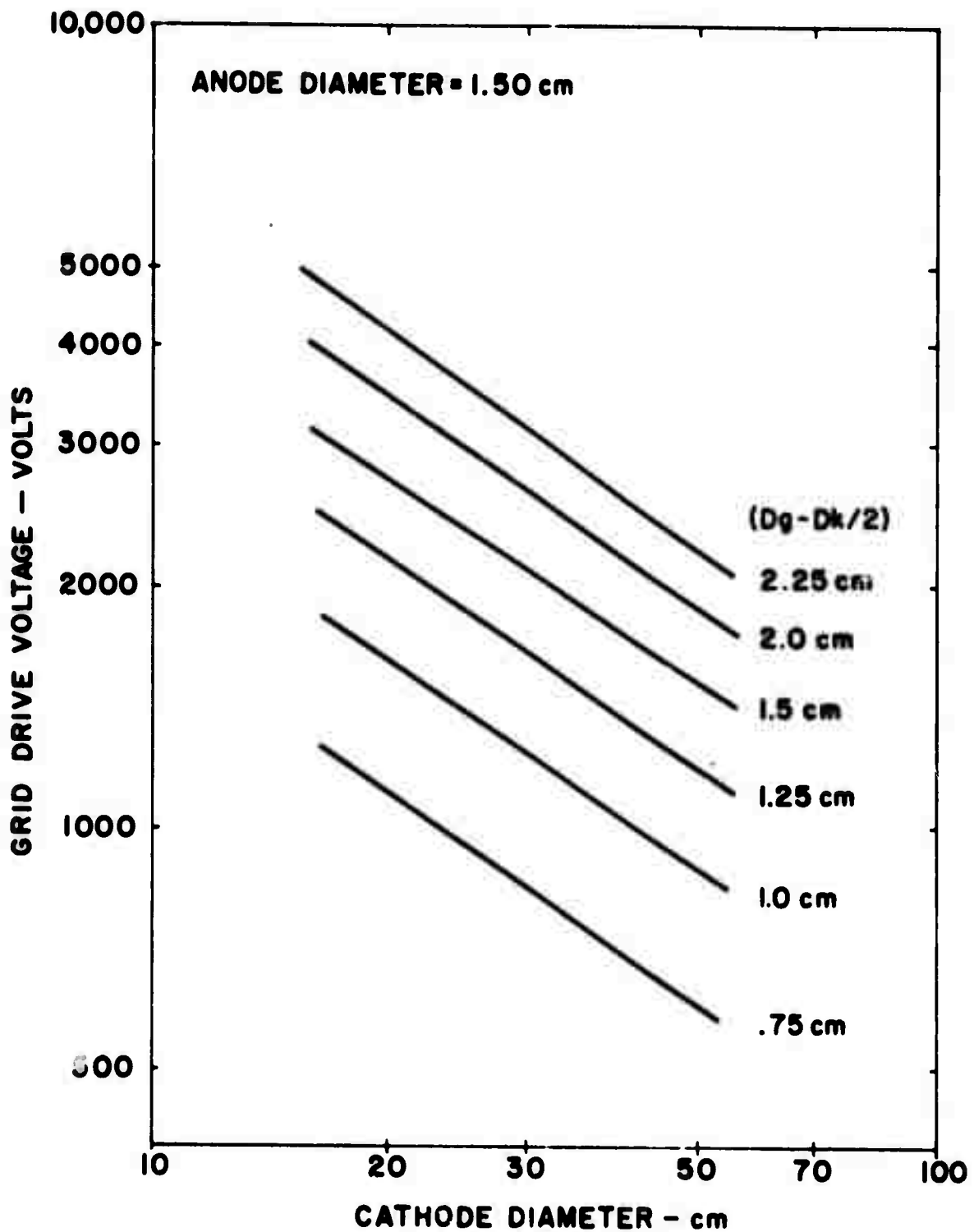
The dimensions of a design satisfying the criteria are listed below:

| <u>Dimension</u> | <u>Metric</u> | <u>English</u> |
|----------------------------|---------------|----------------|
| Length of emitter/cathode | 5m | 197 in. |
| Diameter of emitter | 35.6cm | 14 in. |
| Diameter of Grid | 38.1cm | 15 in. |
| Grid wire diameter | .064cm | .025 in. |
| Number of axial bars | 360 | |
| Screening Fraction of grid | .266 | |
| Anode (Foil) diameter | 1.5m | 59 in. |

This triode would have a grid amplification factor of 850, and a perveance of 0.08 amperes per volt to the $3/2$ power.

The grid bias necessary to cut off the tube between current pulses would be $E_b/\mu = -175$ volts. The total cathode current, assuming 50 percent loss to grid current and foil holder interception and a current density of 10 milliamperes per square centimeter through the foil, would be 4700 amperes. From the Child-Langmuir equation, the peak cathode to grid voltage will be:

$E_{cl} = (4700/.08)^{2/3} - (1.5 \times 10^5 / 850) = 1335$ volts and the peak grid drive voltage will be 1510 volts.



DRIVE VOLTAGE FOR CYLINDRICAL TRIODE

FIG. 6

Grid Current

Although the grid will be positive during the pulse, the grid current will not be excessive. The potential at the grid-radius in the absence of the grid, the "natural potential", would be:

$$V_g' = E_b \frac{\ln(D_g/D_k)}{\ln(D_p/D_k)}$$

At $E_b = 150\text{KV}$, V_g' is +7100 volts. Thus there is a potential depression at the grid plane and the fraction of current intercepted by the grid will be less than the screening fraction of the grid and will be further decreased by secondary electrons emitted from the grid. Empirical data from power grid tubes indicate that the grid current will be less than 20 percent of the total current at these voltages.

Planar Triode Design

An alternate design for the cylindrical gun utilizes, instead of a pair of coaxial electrodes, an assembly of planar electrodes mounted on a prismatic supporting core. The grid and cathode would be made of many parallel bars suspended in tension.

EIMAC is building a two-section planar tetrode electron gun for Lawrence Livermore Laboratories. This gun is designed to deliver a 200KV electron beam, 10 x 100 centimeters in area at up to 2 amperes per square centimeter in a high-duty pulsed mode and can do this for an indefinite period of time.

Figure 7 shows one section of a model of this gun, partially assembled. The supports and bars of the filament (emitter) and control grid and cathode are visible; the bars are fabricated separately and can be removed and replaced without disturbing other bars. Each bar is individually tensioned. This is especially important in the case of filament bars which expand approximately 1 percent on heating from room temperature to operating temperature.

The base (or mounting) structure to which the electrode suspension parts are attached is water cooled to permit continuous operation of the filament.

Vibration of tensioned filaments

The equation for the frequency of lateral vibration of a stretched string in tension is: *

*J.P. Den Hartog, "Mechanical Vibrations", McGraw-Hill, N.Y., 1947, P.175.

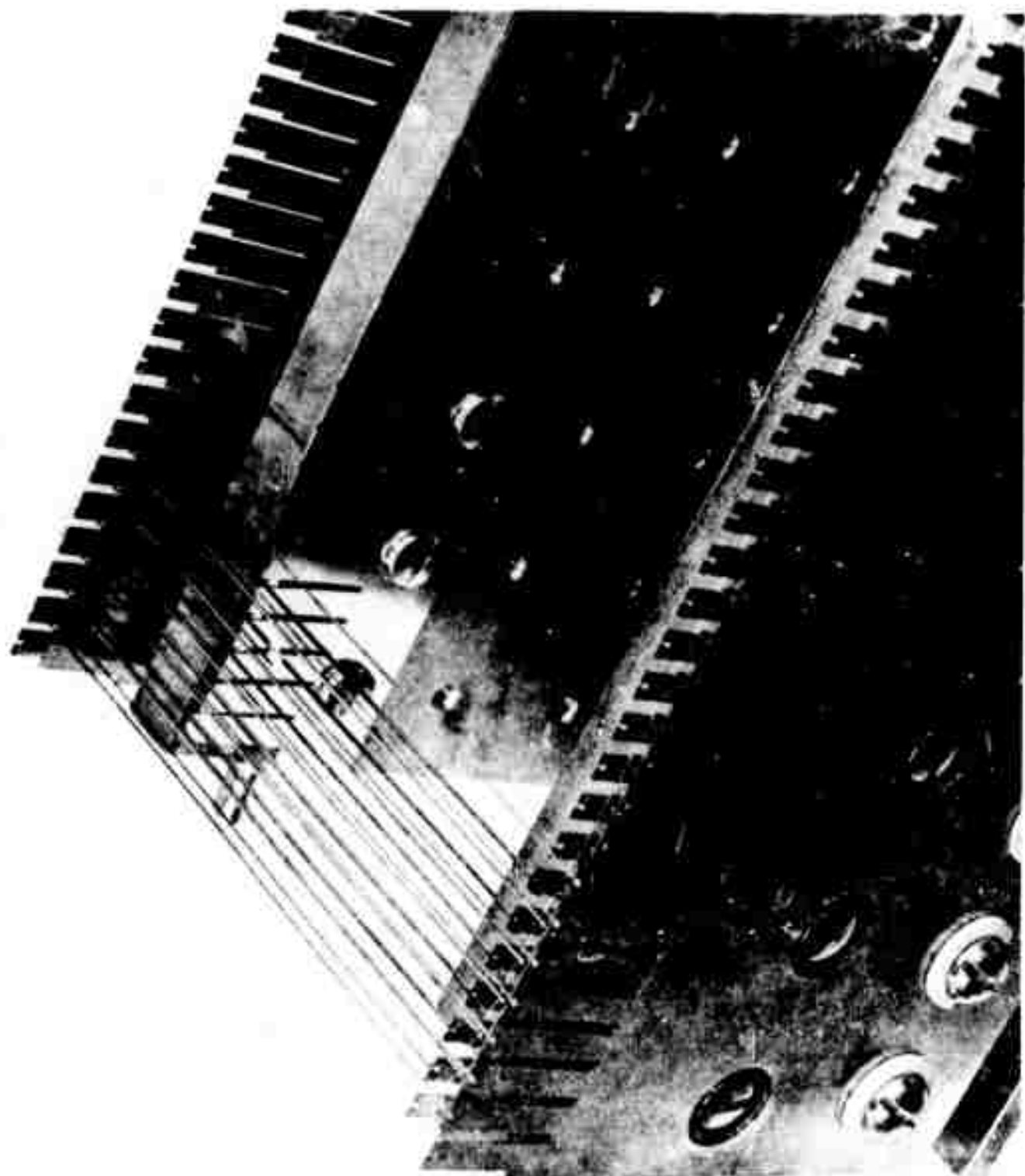


FIGURE 7. A. TOLSON, THE FATHER OF THE FBI, IN THE FBI OFFICE, WASHINGTON, D.C.

$$f_n = \frac{n}{l} \sqrt{\frac{T}{m}}, \quad n = 1, 2, 3.$$

where m = mass per unit length

T = tension

l = length

n = mode number

Inserting the values for tungsten we have, for the fundamental ($n = 1$).

$$f_n = \frac{13.2}{l d} \sqrt{T} \quad \text{Hertz}$$

If T is in pounds, l and d in inches

The tensile stress in the filament is:

$$s = \frac{T}{\frac{\pi}{4} d^2} \quad \text{psi}$$

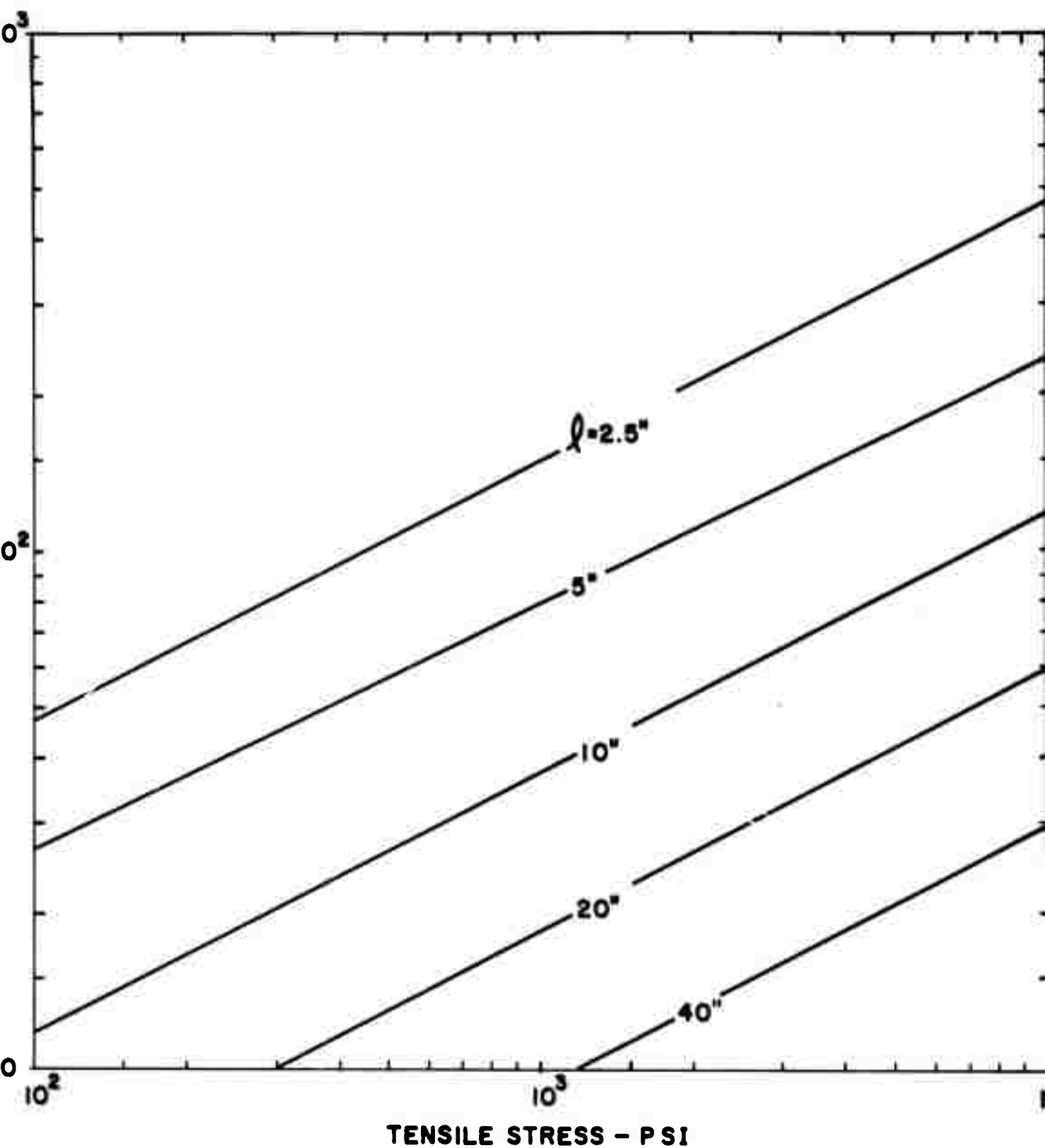
Combining the last two equations:

$$s = .0073 n (l f_n)^2 \quad \text{psi}$$

This expression has been plotted in the graph of Figure 8 which shows fundamental ($n = 1$) resonance frequency versus tensile stress for filaments of constant length.

As an example, a 10 inch long thoriated-tungsten filament bar will be stressed to 4000 psi for a natural frequency of 75 Hertz. This is a marginal loading at an operating temperature of 2000 degrees Kelvin.

A 20 inch long filament would be loaded to more than 10,000 psi for a natural frequency of only 60 Hertz. This would be too high^a stress for reliable operation, particularly after the wire has been carburized and recrystallized in service.



TENSIONED TUNGSTEN FILAMENTS NATURAL
FREQUENCY vs TENSILE STRESS IN WIRE
FOR VARIOUS LENGTHS

FIG. 8

Thus, a straight-wire, tensioned filament structure must use many short sections of filament wire.

Cathode for Planar Triode

The straight-bar tensioned filament can be compared to the 14 inch diameter mesh filament which was described in a previous section.

The total power required for 6280 amperes emission (anode diameter of 2 meters) is 182KW at an operating temperature of 1900 degrees Kelvin.

Using a filament bar 10 inches long and 0.016 inches diameter with 0.5 pounds of tension, the fundamental resonant frequency would be 59 Hertz. 2840 bars would be required, each carrying 7.5 amperes at 8.5 volts. If the filaments were connected in pairs, the total current would be 10,650 amperes at 17 volts.

High tension will result in higher resonant frequency at the expense of increased stress. One pound tension will give a 84 Hertz frequency, but the stress would be 5000 psi which is nearly equal to the creep strength of thoriated tungsten at the operating temperature.

Bonded Electron Windows

Large area electron windows made of 20 to 40 micron thick metal foils have presented problems in materials procurement and application to the e-beam excited lasers. Dimensions and shape (flatness) are hard to control in large widths; pinholes and cracks appear unpredictably. Typically, the foil sheet is sealed to a supporting metal grid at the edges with a bolted compression seal using an organic or metal gasket. These seals have a large perimeter and the gasket and bolts occupy a large portion of the available area. A defect in the foil, no matter how slight, requires replacement of the entire piece of foil. In addition, the support must have deep narrow slots or holes which are unfavorable to transmission of electrons, particularly if the trajectories are curved due to the presence of magnetic fields. If the size of a unit window is reduced, smaller width foil of better quality can be used but a multiplicity of windows would result in large areas lost to seals if flanged, bolted, compression seals were used. However, titanium and titanium alloys can be brazed or diffusion bonded in vacuum; these joints require very little area for sealing.

It may be feasible to make the electron window out of many small circular windows; each brazed to a sealing ring and pre-tested for vacuum tightness at operating temperature and pressure before use in a window assembly. The depth-to-aperture width ratio would be better than a slotted or drilled large foil window support. If one or more windows fail, they could be replaced individually.

A perforated backing of titanium, nickel, or stainless steel sheet could be bonded to the foil to provide strength and thermal conductivity to the support structure.

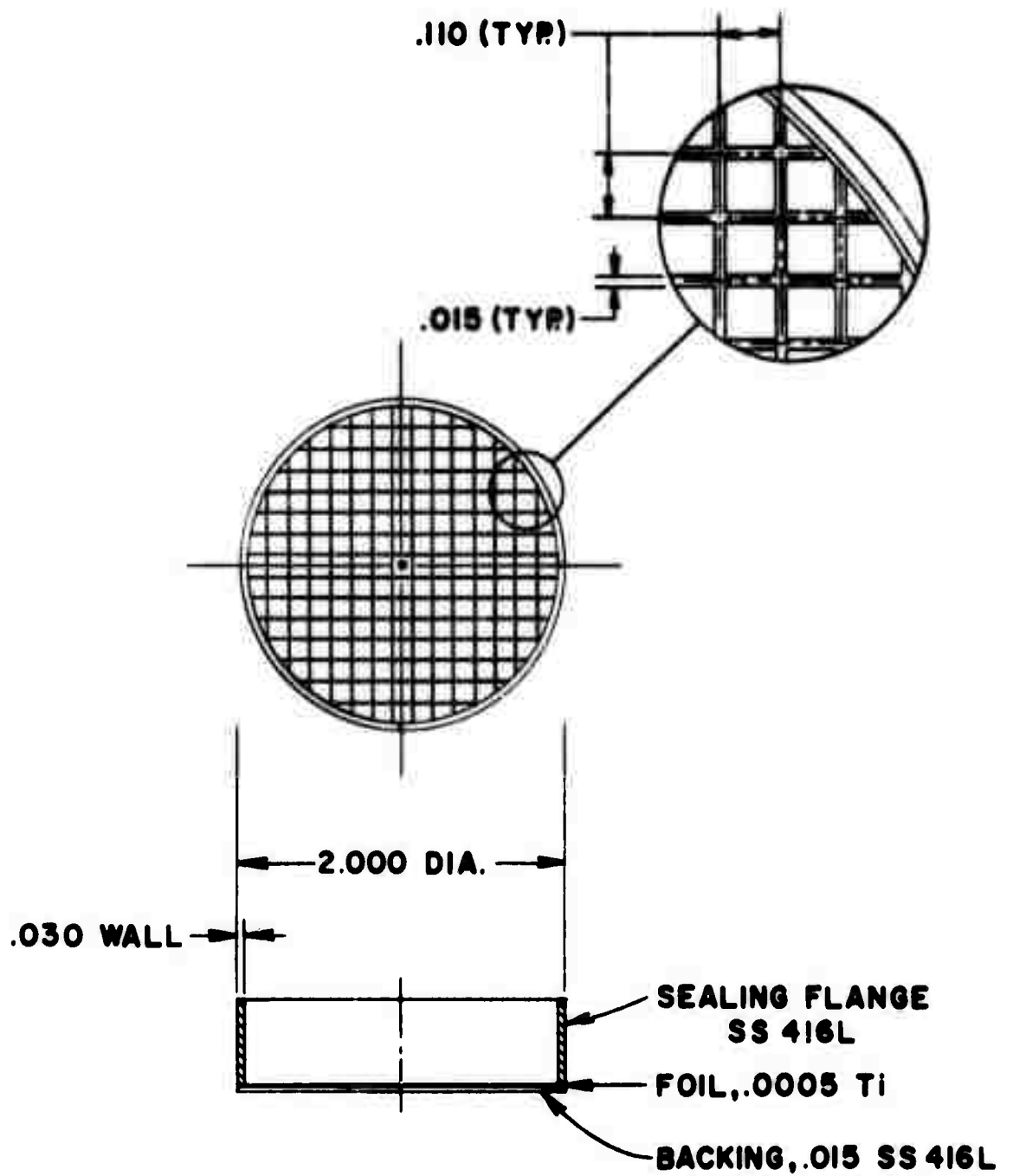
Bonding Experiments

Some experimental window assemblies were made and tested. The window material was 40 micron (.001 inch) titanium A70 and Ti 6Al4V (6 percent aluminum, 4 percent vanadium, balance titanium) alloy. Two methods were used to join the foil to sealing rings, diffusion bonding in vacuum and braze with silver and with silver-copper in eutectic proportions. The sealing rings were, variously, nickel, SS416L, and Kovar alloy, 1 inch diameter with 0.030 inch wall thickness. The assemblies, after bonding, were welded into canisters, baked out at 400 degrees Celsius for 2 hours, then pressure-tested with bottled N₂ at 300 degrees Celsius with a Pirani vacuum gage attached for a leak indicator.

Light assemblies were obtained with A70 titanium diffusion bonded to nickel or SS416L rings. These withstood 60 to 75 psi (abs.) pressure at 300 degrees C. Vacuum-tight assemblies were also obtained using A70 or Ti6Al4V foils brazed to Ni or SS416L sealing rings, leaking at 60 psi (abs.) pressure differential at 300 degrees C. The tight brazed assemblies were made with 0.002 inch thick foil washers of 72 Ag 28Cu copper-silver alloy and with very thin plated copper and silver layers in the eutectic proportion. Silver and copper were tried separately, but attacked the titanium too strongly at the melting temperatures.

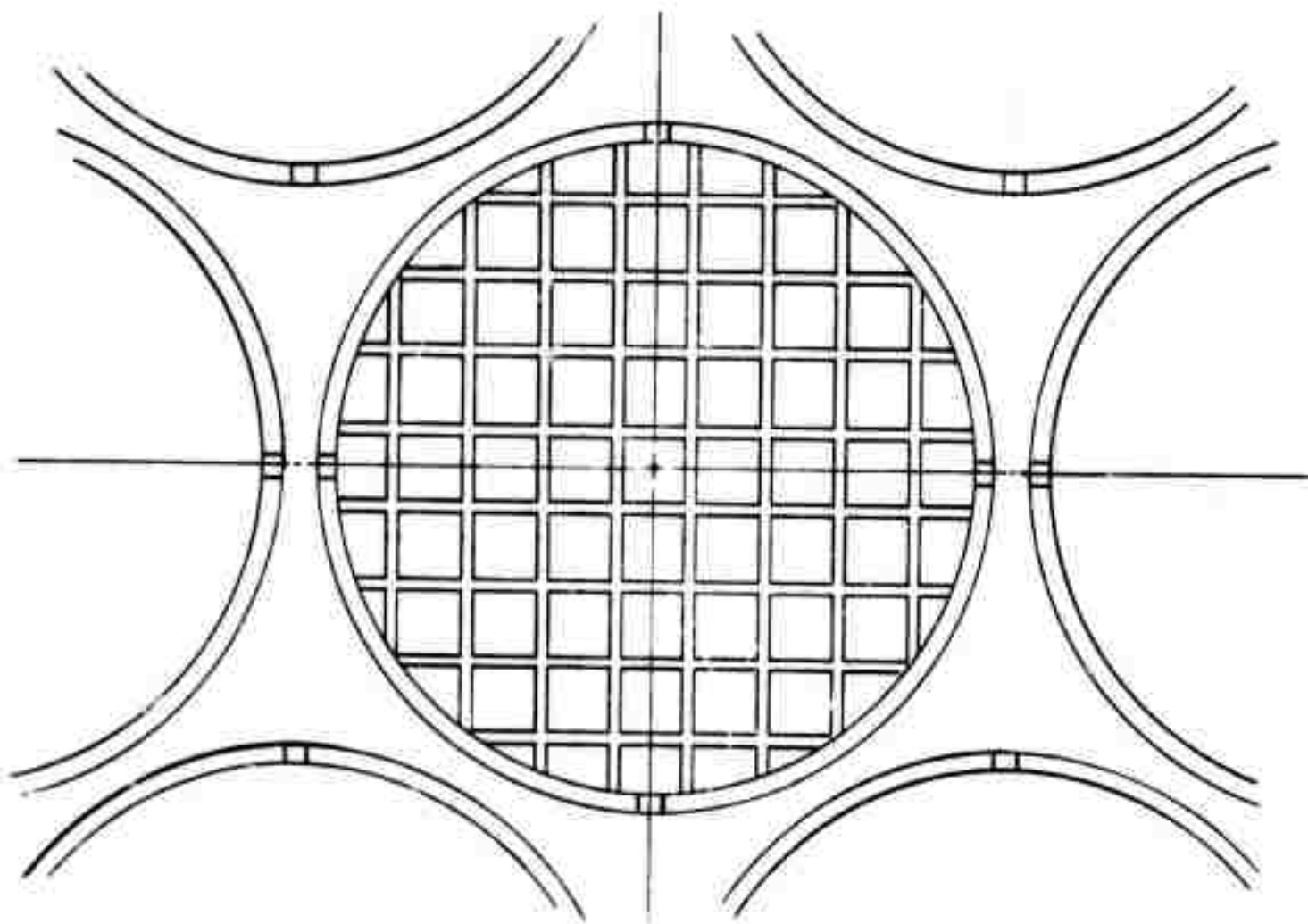
Reinforced Window Foil

It should be possible to make either diffusion or brazed bonds to a perforated backing/reinforcing sheet. Figure 9 shows a conceptual drawing of a window assembly, 2 inches diameter with 0.0005 inch (20 micron) foil bonded to 0.015 inch thick etched stainless-steel backing plate. Figure 10 shows a bonded window-to-envelope assembly method with replaceable windows.



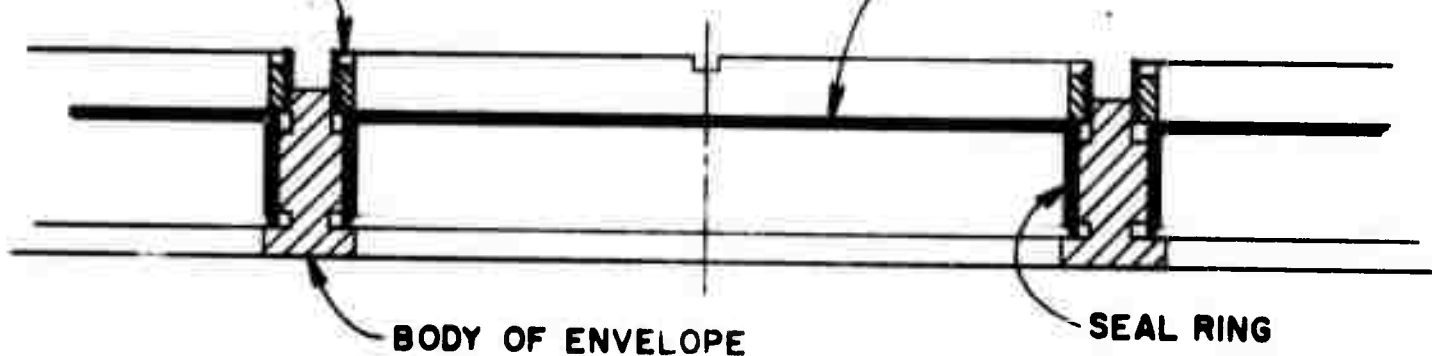
BONDED WINDOW ASSEMBLY

FIG. 9



**THREADED
SEALING RING**

BONDED WINDOW



**WINDOW -- TO -- ENVELOPE ASSEMBLY
WITH REMOVEABLE WINDOW**

FIG. 10

3.0 CONCLUSIONS AND RECOMMENDATIONS

Cathode Materials

Thoriated-tungsten wire with light carburization is the best choice of cathode material with respect to strength, life, and electron emission efficiency.

Structures

A self-supporting, welded, thoriated-tungsten wire mesh cathode, coaxial with a welded grid assembly will have good emission uniformity and resistance to shock. Large tetrodes and triodes using such cathodes in series are being manufactured; these are approximately 60 percent of the minimum required module size. However, no large numbers of these cathodes have been assembled in any one device.

A 10 x 100cm planar array tetrode gun structure is being built on another program to demonstrate feasibility of continuous operation in a high power electron gun. Approximately 30 modules of this size would be required in the large cylindrical electron gun application. The planar type gun would be easier to maintain and repair but would be considerably more complex and require a great many more parts than a coaxial triode gun.

Electron window foils have been bonded to supporting rings with vacuum-tight seals. They have been successfully tested at high temperature. These use small pieces of metal foil which are generally of higher quality than very large foils. It may be possible to use very thin foils bonded to a grid-like reinforcement and obtain a large area, shallow, window which will have

better transmission and lower electron energy loss than existing designs.

The following design solutions should be provided in order to obtain better electron gun performance and life in the required size:

- a. Bakeout of entire structure at 400 degrees Celsius, minimum, including electrodes, insulators and envelope.
- b. Fabrication of small window foil modules and testing prior to use.
- c. Assembly of a large number of filamentary cathodes and grid modules into a single gun, and provision for replacement of defective units.
- d. Provide adequate fluid cooling of cathode so that operation time is not dependent on heat capacity of the parts.

APPENDIX A

Mesh Filament Structure - Vibration

The mesh filament will be required to function following exposure to shock and vibration environments on the support structure. These energy inputs are either the result of shipping and handling or due to acoustic coupling between the lasing gas and the structure.

Equations were derived for the longitudinal spring constant of mesh filaments, the weight of the filament, and the resulting longitudinal resonant frequency. Three sample mesh filaments were assembled, (Nos. 1, 3 and 52) and vibrated. Their resonant frequencies were determined and compared to the theoretical values.

The equation for the longitudinal spring constant (k) of a mesh filament is:

$$K = \frac{3\pi}{16} E \frac{d^4}{b^3} \left(\frac{NH}{NV} \right) \text{ lb/inch}$$

where E = Modulus of elasticity at operating (or testing) temperature, lb/in²

d = Diameter of filament wire, inch

b = length of side of mesh parallelogram, inches

NH = Number of filament wires cut by a radial plane across the mesh filament

NV = Number of filament wires on one side of the mesh filament cut by a longitudinal plane across the mesh filament

For filaments No.1 & No.3 the theoretical spring constant was calculated as 7.21 lb/in and for filament No.52 it was calculated as 31.14 lb/in. The actual spring constant was found empirically

to be 43.14 lb/in. for filament No. 52. Since the actual spring constant was slightly higher (due to the effects of the constraining end rings) than the calculated value, the actual longitudinal resonant frequency of the filament should also be higher than the theoretical values. This is borne out in the Summary in Table I.

The weight of the mesh filaments must also be determined before calculating the theoretical resonant frequencies. This is given by the equation:

$$W = \frac{\pi}{4} d^2 \rho N H \frac{l}{\sin \theta} \quad \text{lb}$$

where: d = wire diameter

ρ = density of the filament wire, lb/in³

l = mesh filament overall length, inch
(or height of the cage)

θ = pitch angle of the mesh filament wires, degrees

The other symbols are defined above. Filaments No. 1 and No. 3 were calculated to weigh 0.46 lb each and filament No. 52 was calculated to be 0.040 lb.

The equation for the longitudinal resonant frequency is:

$$f_n = \frac{n}{2} \sqrt{\frac{Kg}{W}}$$

where: f_n = Resonant frequency, hertz

n = Resonant mode (= 1 for fundamental)

K = Spring constant

g = Acceleration of gravity, inch/sec²

W = Weight of the mesh filament, lb.

TABLE I

SUMMARY OF STRUCTURE DETAIL, THEORETICAL RESONANCE FREQUENCY AND
ACTUAL TEST DATA.

| Mesh Filament | Diameter of Fila- ment Wire (d) (Inch) | Length of Mesh Side (b) (Inch) | Wires, Horizontal Plane (NH) | Wires, Vertical Plane (NV) | Mesh Fila- ment Cage Length (ℓ) (Inch) | Pitch Angle (θ) (Degrees) | Direc- tion of Motion | Resonant Frequency (Hz) | |
|------------------|--|---|---------------------------------------|-------------------------------------|---|---|--------------------------------|----------------------------|-----------------|
| | | | | | | | | Theoret- retical | Actual |
| #1 | .0100 | .456 | 64 | 32 | 5.75 | 25.6° | Longi- tudinal Lateral | 123 | No Data |
| #3 | .0100 | .434 | 64 | 32 | 5.75 | 25.6° | Longi- tudinal Lateral | 123 | >2000 149 |
| #52 | .0115 | .238 | 44 | 54 | 5.56 | 25.6° | Longi- tudinal Lateral | 274 | See Text 293 |
| | | | | | | | | --- | >800 |

The longitudinal resonant frequency for filaments No. 1 and No. 3 was calculated as 123Hz and the actual value found for filament No. 3 was 149Hz; slightly higher as expected. No empirical data was taken on filament No. 1 in this direction.

The longitudinal resonant frequency for filament No. 52 was calculated as 274 Hz and the actual value was found to be 293Hz; again slightly higher as expected.

No equation for the theoretical lateral resonant frequency of the mesh filament was derived but actual data were taken on the three mesh filaments. No motion was detected below 2000Hz at 10g input in filament No.1. Very small lateral motion was noted in filament No. 52 above 800Hz. Filament No. 3 demonstrated very mild motion (less than 0.025 inch double amplitude) at 89,109 and 254Hz and no other motion below 500Hz. The lateral motions observed were all with small excursions and were self-dampening. Unless continuous excitation at the resonant frequency were applied it appeared doubtful that these resonances would even be excited.

Table I is a summary of the theoretical and actual resonance data and the mechanical characteristics of the mesh filament structure tested.

Figure 1 is a photograph of mesh filament No. 1.

Figure 2 is a photograph of mesh filament No.52.

Figure 3 is a photograph of mesh filament No.52 mounted on the vibration fixtures used for these tests.

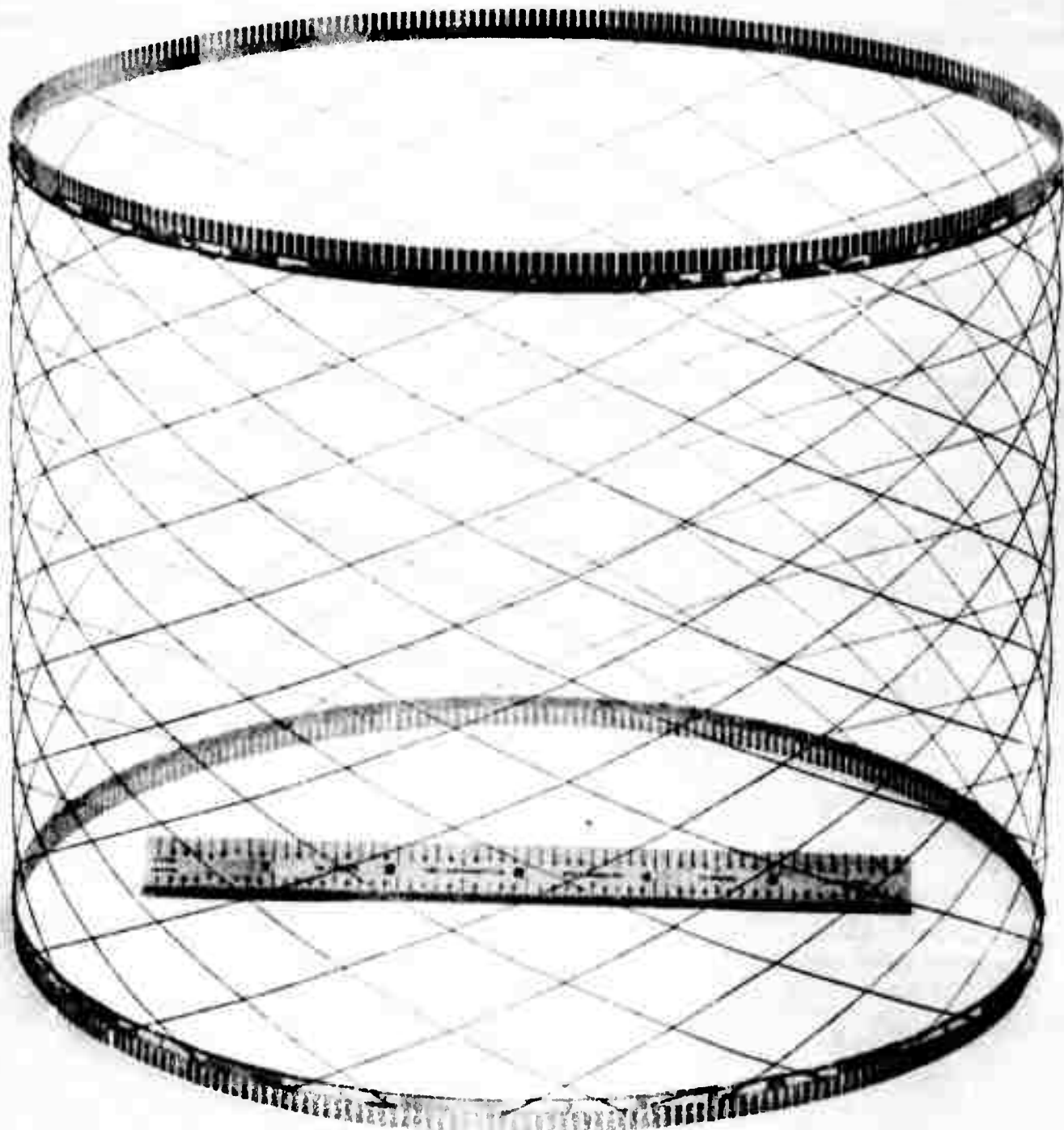


FIGURE 1
MESH FILAMENT #1

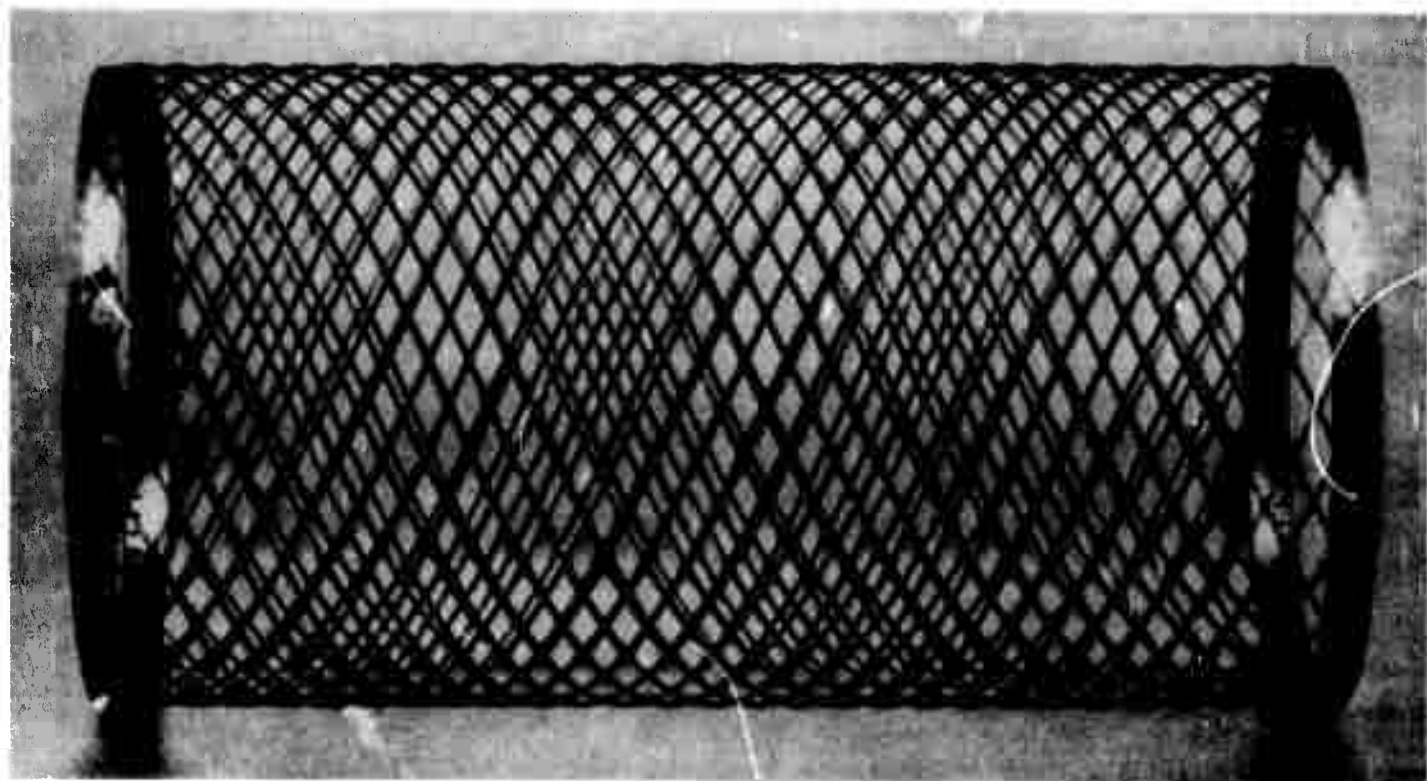


FIGURE 2
MESH FILAMENT #52

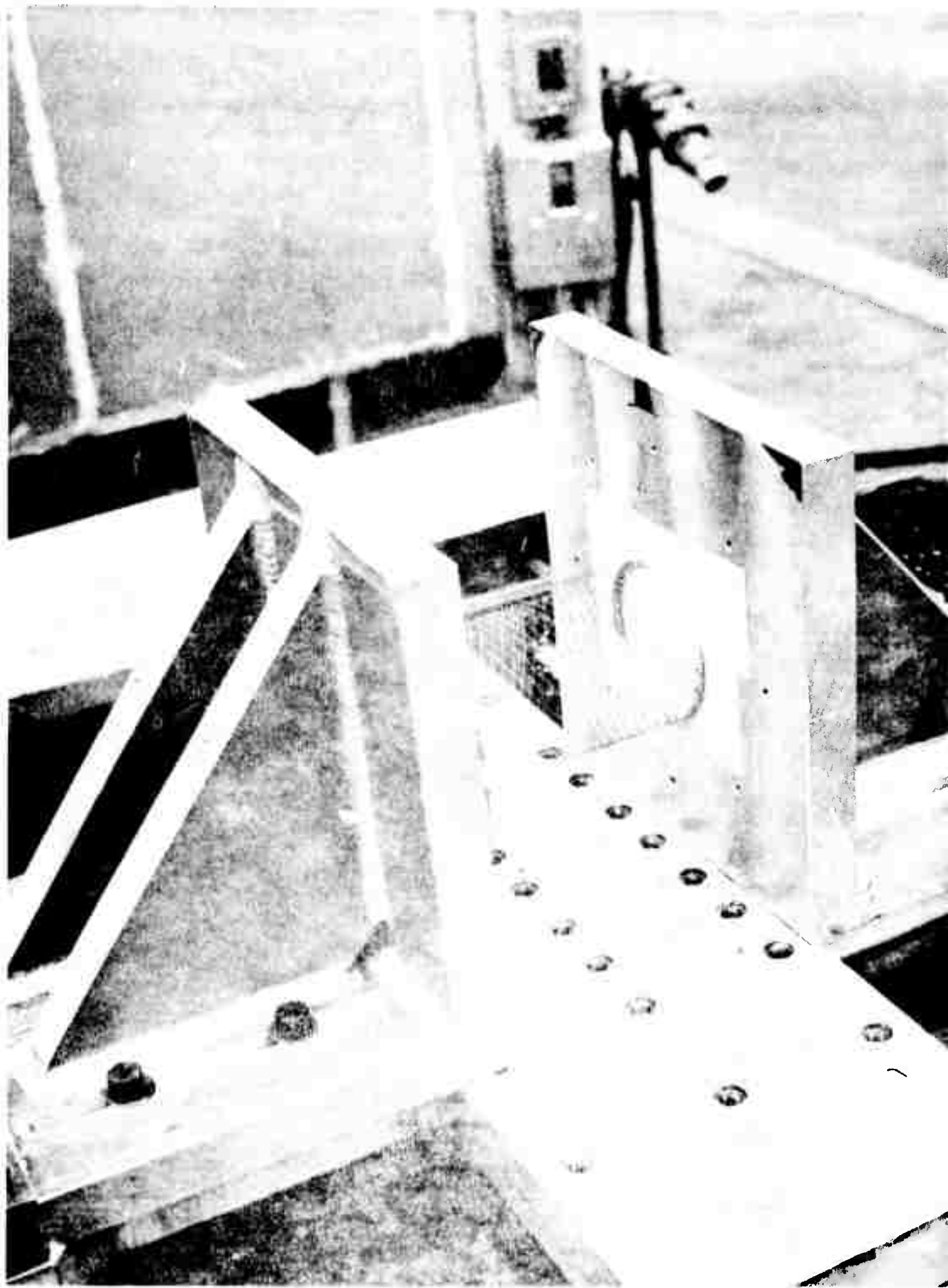


FIGURE 1. Aerial view of the engine.

The testing program assured the project that the longitudinal resonant frequency of the mesh filament can be predicted and that the lateral resonance will probably offer no serious consequences to an operating, full scale E-gun incorporating these filaments.